The Run II Physics Program

John Womersley

Fermi National Accelerator Laboratory, Batavia, Illinois

Representing the CDF and DØ collaborations

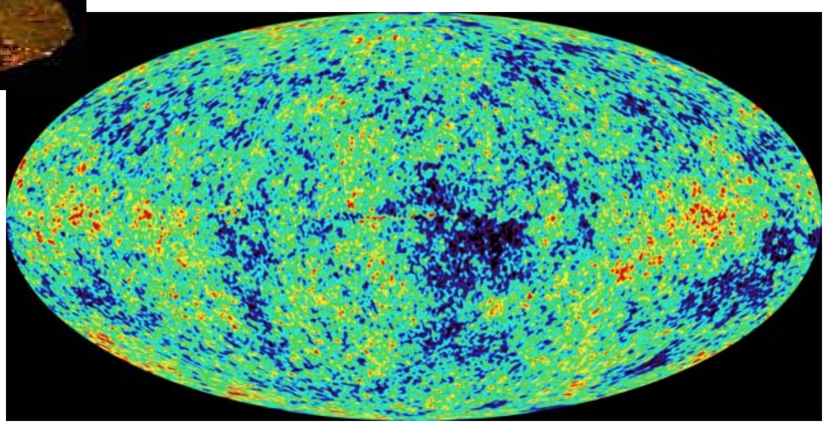
The Run II physics program

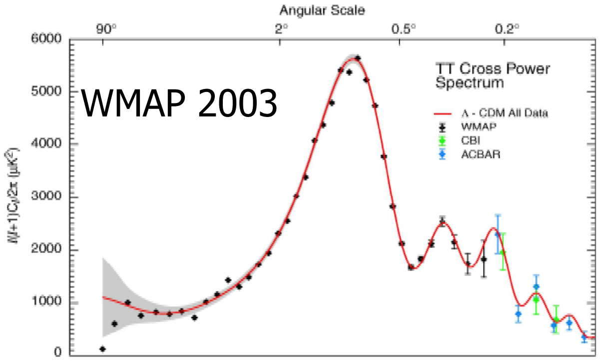
- **A broad physics program which evolves as a function of luminosity**
  - **There is interesting physics at all luminosities, starting now with 50-100 pb^{-1} and continuing through 0.3, 1, 2, 5, 10, 15 fb^{-1}**
- **This physics program has begun**
- **The goal of the collaborations is to**
  - **Maximize this physics program**
  - **Exploit the full potential of the world's highest energy collider and the large investments we have made in the accelerator and detectors**
  - **Lay a firm foundation for the LHC and for future initiatives at the TeV scale**
    - Attract and train the best students in the field
    - Clarify physics requirements
    - An international program in the US - groundwork for the future

Big Questions at the Electroweak Scale

- **The Tevatron is the only accelerator in operation that can help to answer**
  - **What is the structure and what are the symmetries of space-time?**
  - **Why is the weak force weak?**
  - **What is cosmic dark matter made of?**

About six to seven times more mass in the universe (27±4%) than there is baryonic matter (4.4±0.4%)





What is this stuff? How can we get a firmer understanding of it?

Accelerators

- **Run II is the only opportunity to make such a major discovery at an accelerator in the United States**

The program

- The Run II Physics program
  - Confront the standard model through precise measurements
    - The strong interaction, the quark mixing matrix, the electroweak force and the top quark
  - Directly search for particles and forces not yet known
    - Both those predicted (Higgs, supersymmetry, dark matter, extra dimensions) and those that would come as a surprise

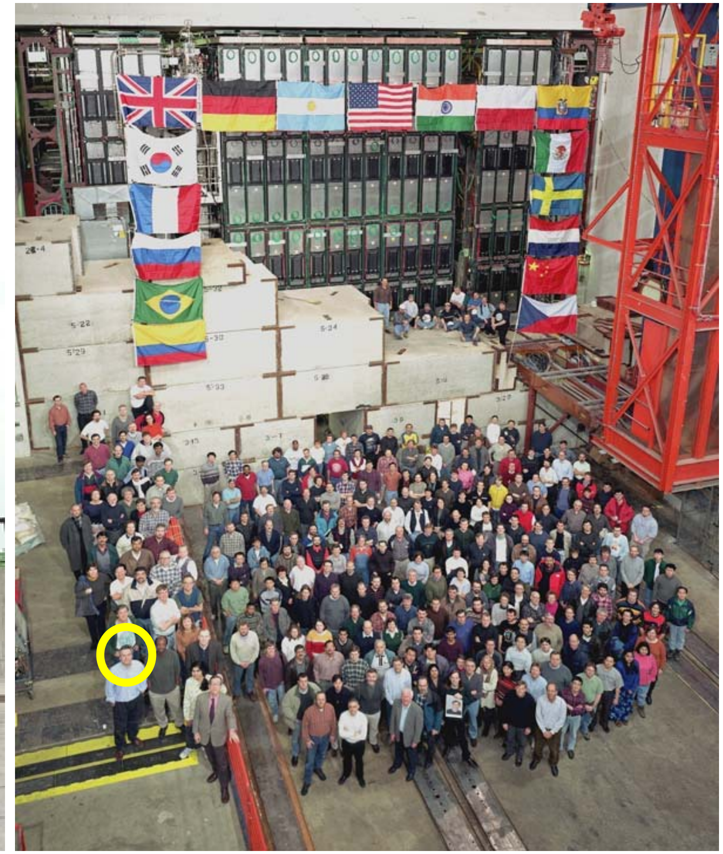
- The program was developed in a series of workshops between 1998 and 2000
  - http://fnth37.fnal.gov/run2.html

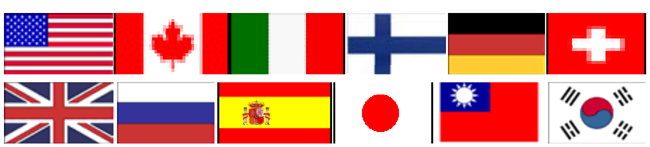
- The program stretches from the GeV scale to the TeV scale

- Here I can attempt only a superficial survey and will concentrate on the physics that gains most from luminosity
  - Illustration of the breadth of the program:
    110 talks from CDF and DØ at APS/DPF meeting in April

Two Worldwide Collaborations

More than 50% non-US: a central part of the world HEP program



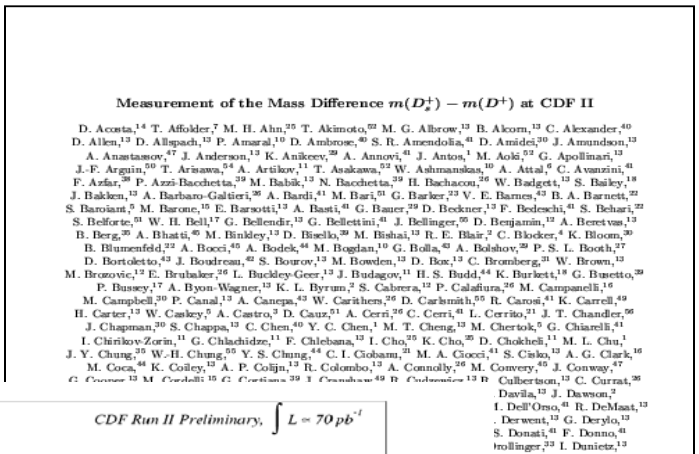


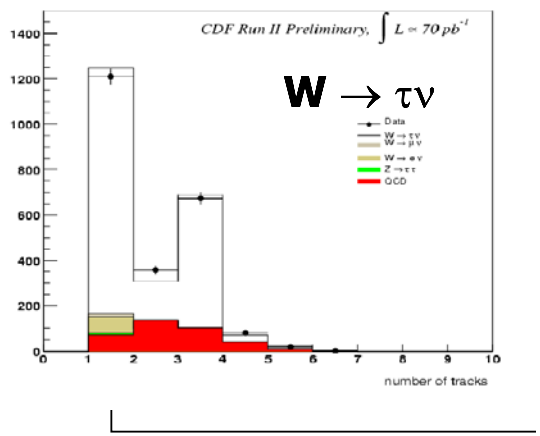
12 countries, 59 institutions
706 physicists

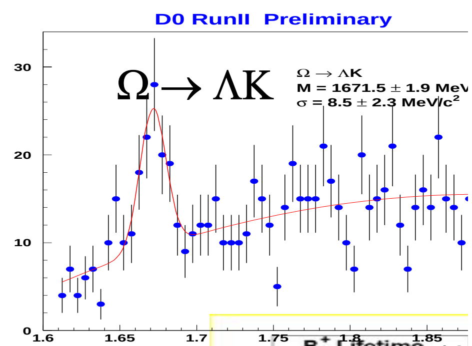
~~18~~ 19 countries, ~~78~~ 80 institutions
~~664~~ 670 physicists

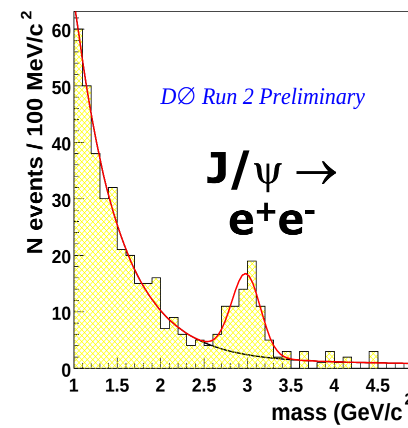
Operations Status

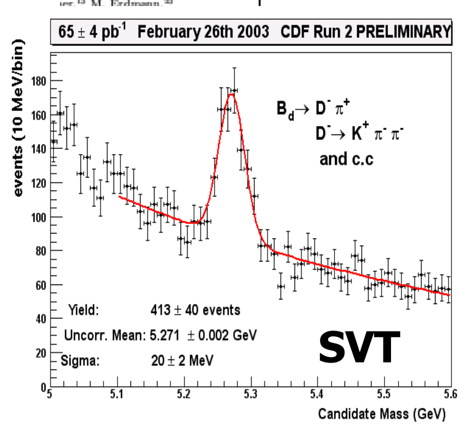
- Both experiments are operating well and recording physics quality data with high (~ 90%) efficiency
- 100-140 pb^{-1} being used for analysis for summer 2003
- Data are being reconstructed within a few days

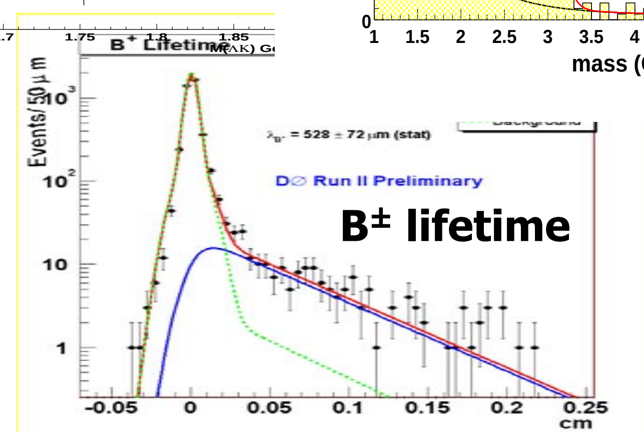

Measurement of the Mass Difference $m(D_s^+) - m(D^+)$ at CDF II





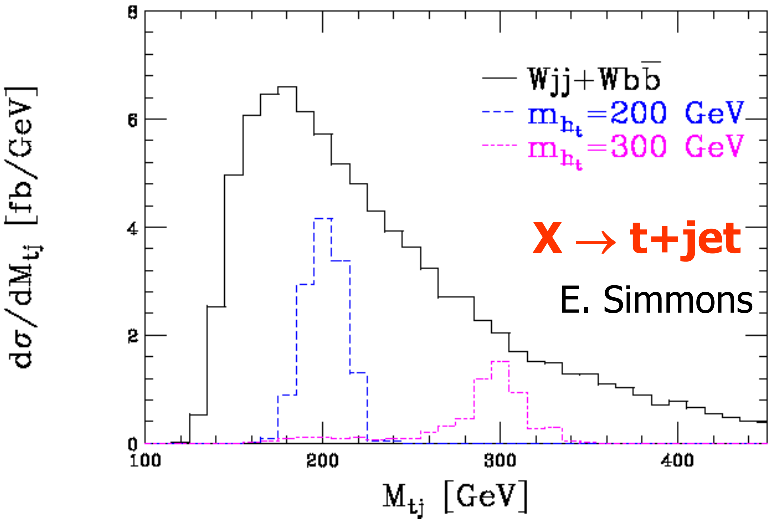




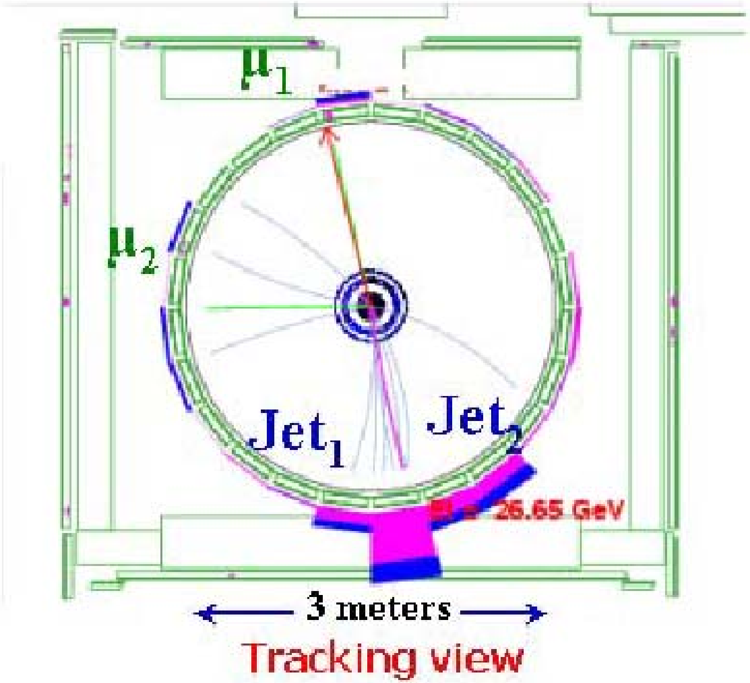


The Top Quark

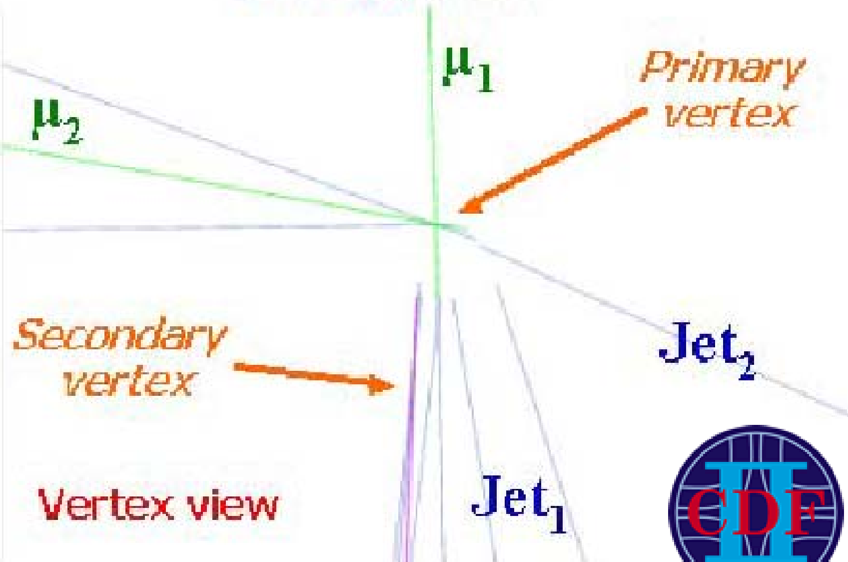
- Why, alone among the elementary fermions, does the top quark couple strongly to the Higgs field?
  - Is nature giving us a hint here?
    - Is the mechanism of fermion mass generation indeed the same as that of EW symmetry breaking?
  - The top is a window to the origin of fermion masses
- The Tevatron Collider is the world's only source of top quarks
- We are measuring its
  - Mass
  - Production cross section
  - Spin
    - Through top-antitop spin correlations
  - Electroweak properties
    - Through single top production
- Any surprises, anomalies?



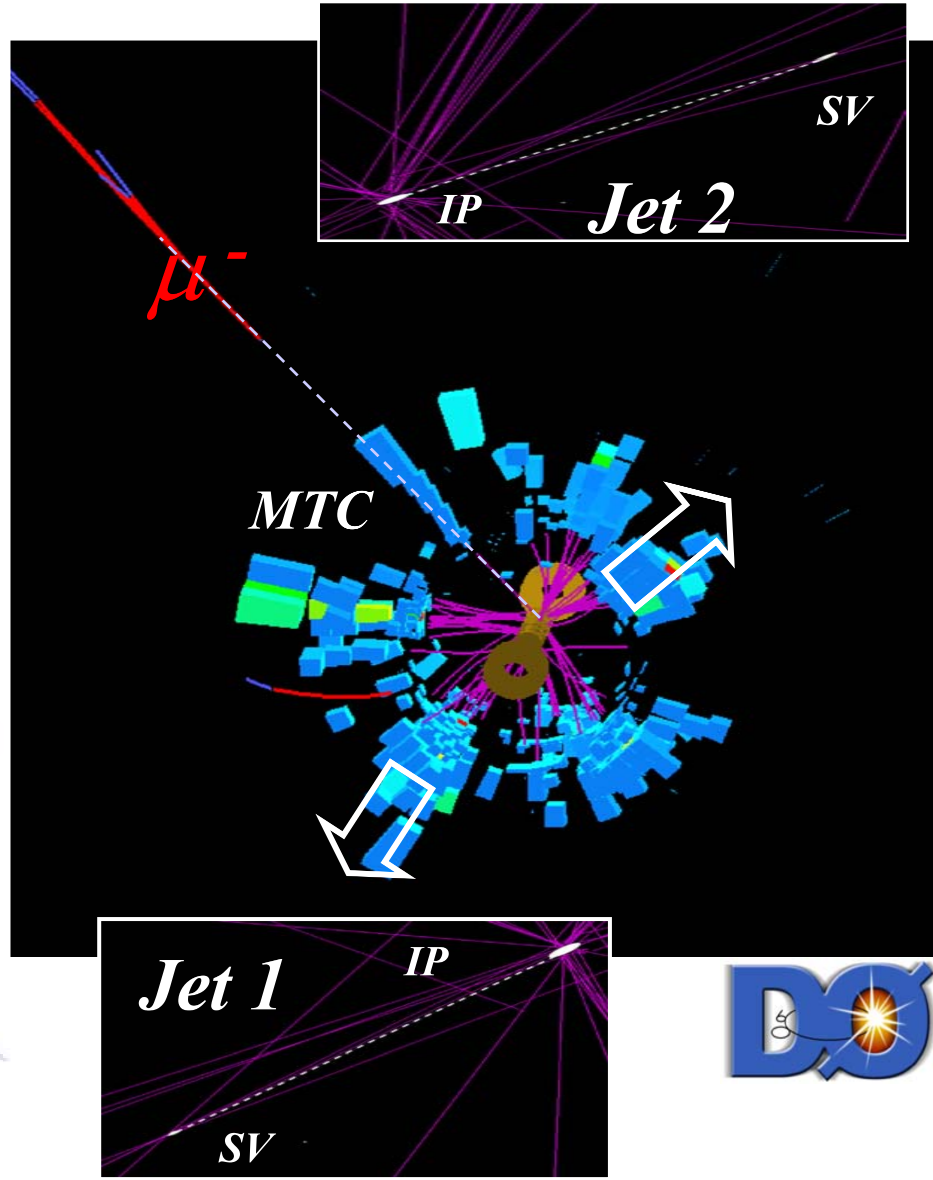
The Run II Top Physics Program has begun



μ_1
μ_2
Jet$_1$
Jet$_2$
26.65 GeV
3 meters
Tracking view

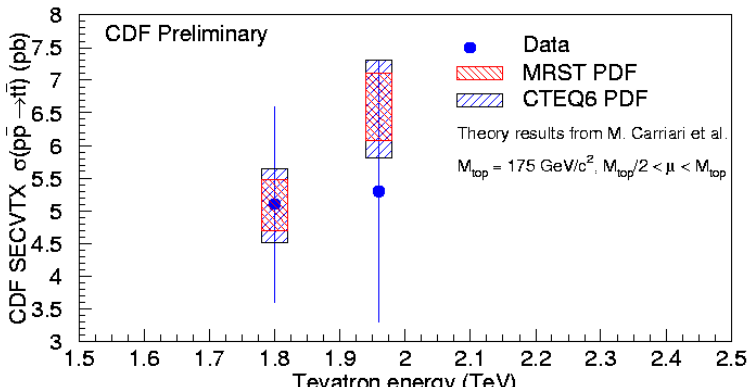


μ_1
μ_2
Primary vertex
Secondary vertex
Jet$_2$
Jet$_1$
Vertex view



SV
IP
Jet 2
μ^-
MTC
Jet 1
IP
SV

The top quark rediscovered, 2003

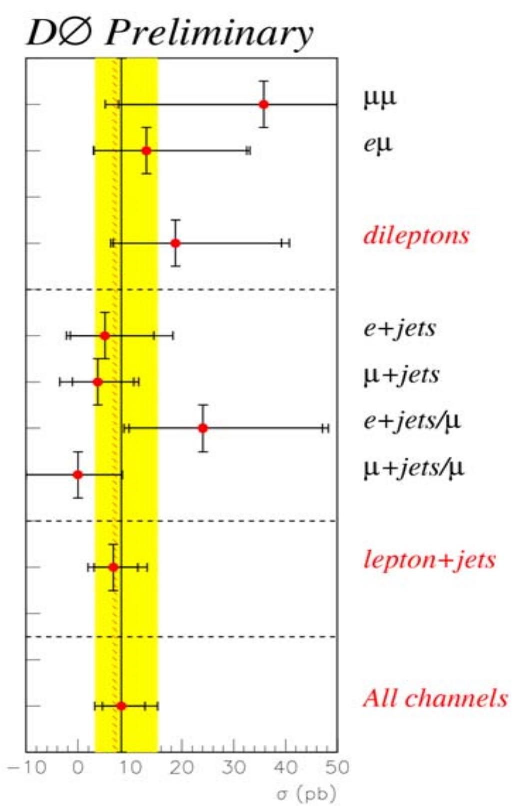


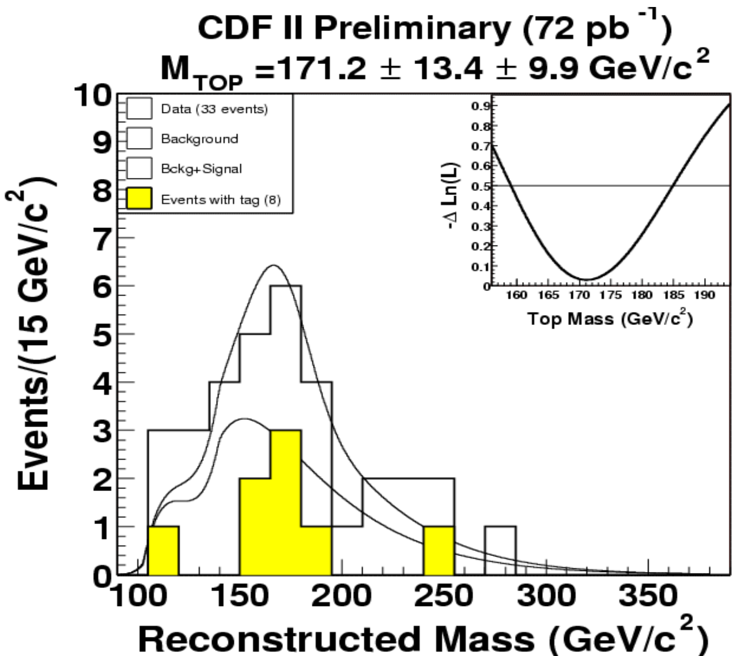
Cross section

CDF dileptons $\sigma = 13.2 \pm 5.9_{stat} \pm 1.5_{sys}$ *pb*

CDF l + jets $\sigma = 5.3 \pm 1.9_{stat} \pm 0.8_{sys} \pm 0.8_{lum}$ *pb*

DØ (comb.) $\sigma = 8.4^{+4.5}_{-3.7}(stat)\,^{+5.3}_{-3.5}(syst) \pm 0.8(lumi)pb$



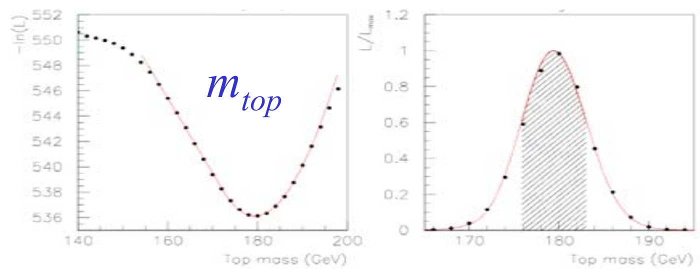


CDF mass

$M_{top} = 171.2^{+14.4}_{-12.5\ stat} \pm 9.9_{sys}$ GeV/c²

Top mass

- **We can look forward to improved precision on m_t in the near future**
  - **More data (few hundred pb^{-1})**
  - **Expect ~ 500 b-tagged lepton+jets events per experiment per fb^{-1}**
    - **cf. World total at end of Run I ~ 50**
- **Improved techniques**
  - **e.g. new DØ Run I mass measurement is equivalent to a factor 2.4 increase in statistics:**



$$m_{top} = 179.9 \pm 3.6 \quad (stat)\ GeV/c^2$$ *(5.6 GeV from PRD 58 052001,1998)*

Improved top mass measurements help to constrain the Higgs mass

Δm_t	l + jets	dilepton
2 fb^{-1}	± 2.7 GeV	± 2.8 GeV
10 fb^{-1}	± 1.6 GeV	± 1.6 GeV

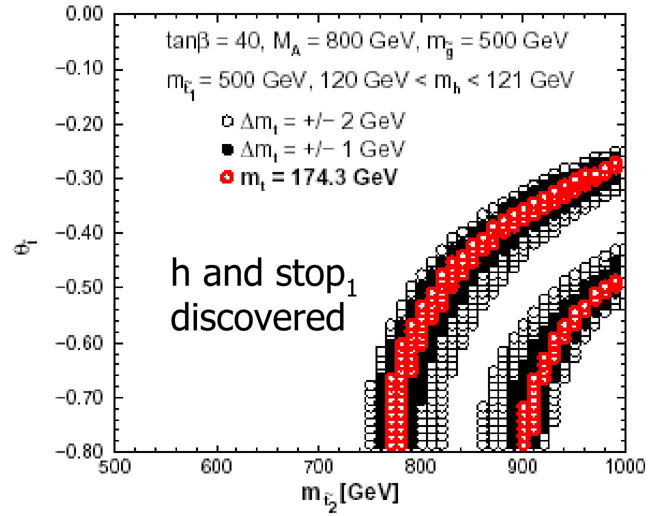
per experiment, using the "classic" technique

[from M. Grunewald et al., hep-ph/0111217 (2001)]

$\boxed{dm_H/dm_t \sim 50\ GeV/4\ GeV}$

Top physics program

- **Precise knowledge of m_t (~1 GeV) will be very useful even after a light Higgs is discovered**
  - **Is it H_{SM} or SUSY h?**
  - **Constrain the stop sector:**
    [M. Beneke et al., hep-ph/0003033]



- **Single top production**
  - **The way to measure top width**
  - **So far unobserved**
  - **With ~ 1 fb^{-1} should be able to see signals for both s and t-channel production (have different sensitivity to new physics)**

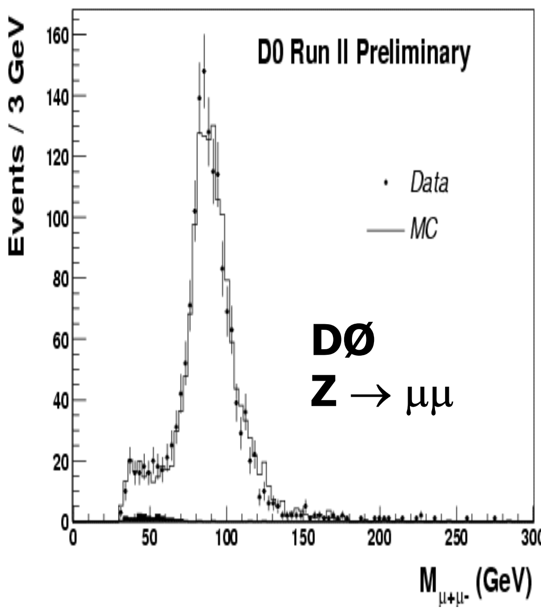
	$\Delta\sigma$ (s)	$\Delta\|V_{tb}\|$(s)	$\Delta\sigma$ (t)	$\Delta\|V_{tb}\|$(t)
2 fb^{-1}	21%	12%	12%	10%
10 fb^{-1}	9%	6%	5%	8%

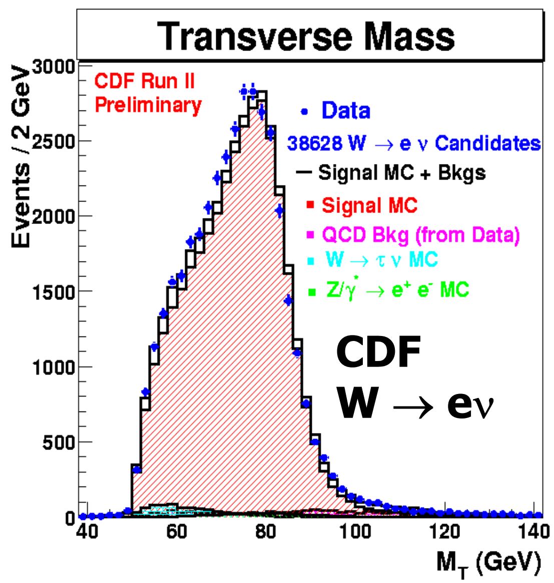
*[scaled from T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. **D58**, 094021 (1998)]*

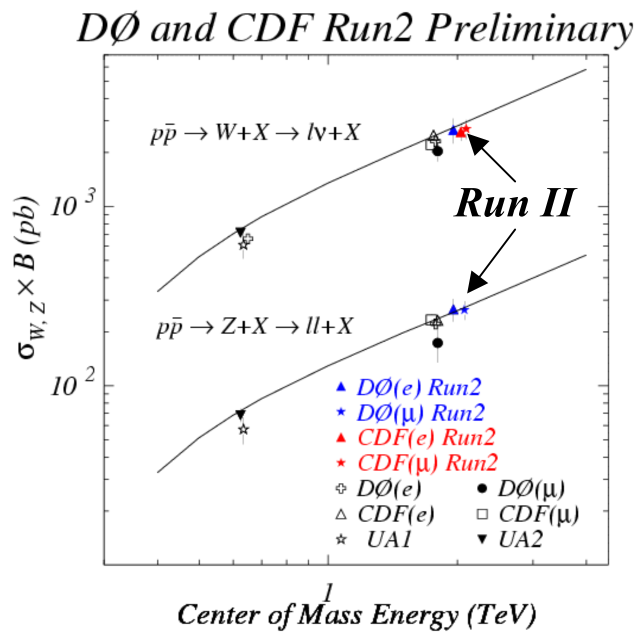
- **Top-antitop spin correlations**
  - **With 2fb^{-1}, distinguish spin-½ from spin-0 but only at the 2σ level**
- **New physics**
  - **$t\bar{t}$ mass, top p_T, rare decays and nonstandard decays, anomalous single top …**

Electroweak Physics

- In Run II we will complement direct searches for new phenomena with indirect probes
  - New particles and forces can be seen indirectly through their effects on electroweak observables.
  - Tightest constraints come from improved determination of the masses of the W and the top quark.
- Both experiments have preliminary results from Run II samples of W and Z candidates:



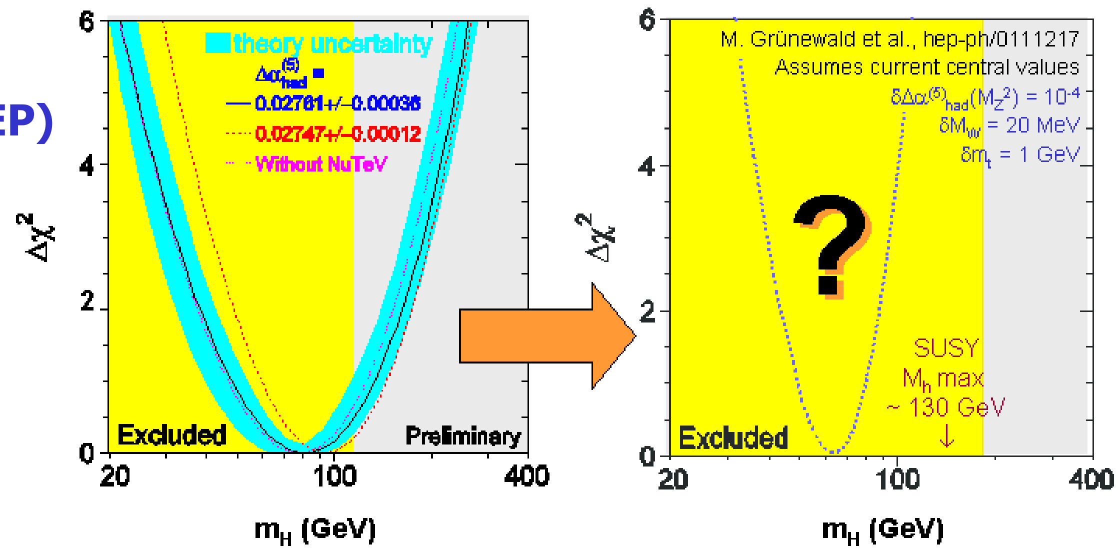




Prospects for W mass

Current knowledge of m_W

- **hadron colliders:**
  - **80 454 ± 59 MeV**
- **World (dominated by LEP)**
  - **80 451 ± 33 MeV**



Run II prospects
(per experiment)

	Δm_W
2 fb^{-1}	**±27 MeV**
10 fb^{-1}	**±18 MeV**

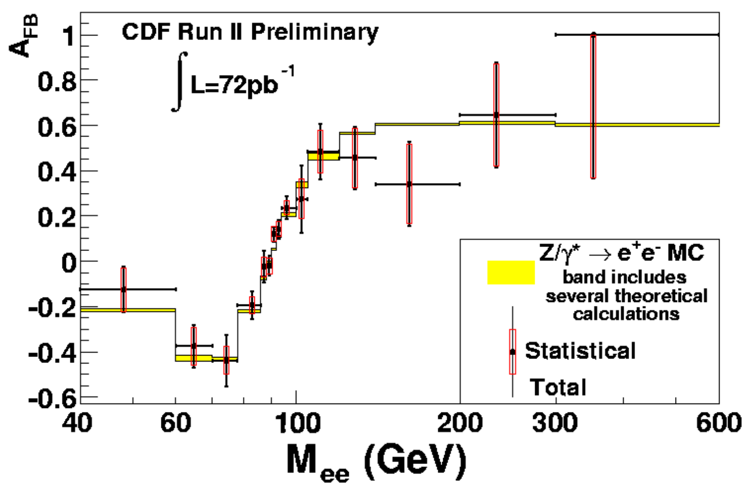
[from M. Grunewald et al., hep-ph/0111217 (2001)]

We have shown we can measure the W mass precisely at the Tevatron, but to improve on LEP will require ~ fb^{-1} datasets - not a short term goal

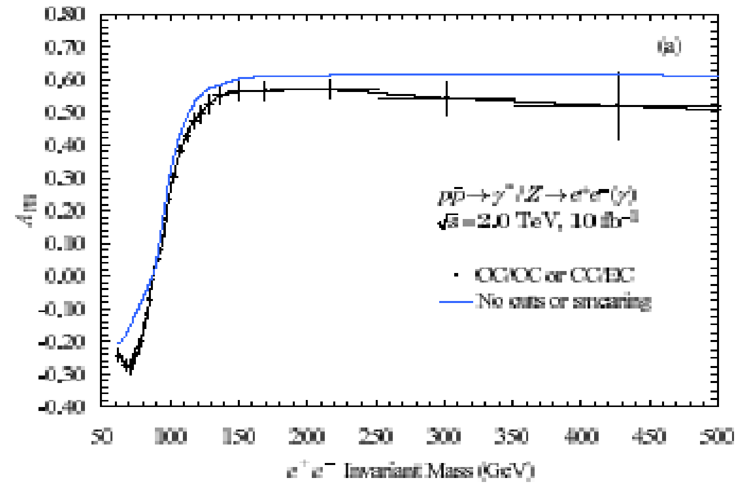
dm_H/dm_W ~ 50 GeV/25 MeV

Other electroweak measurements

- **Forward-backward asymmetry A_{FB} in $Z \rightarrow ee$**



CDF – Paper in preparation



Projection for 10 fb^{-1}

- **measure effective $\sin^2\theta_W$ to 0.0002 (10fb^{-1}) and test γ^*/Z interference at $\sqrt{s}$ much greater than LEP**

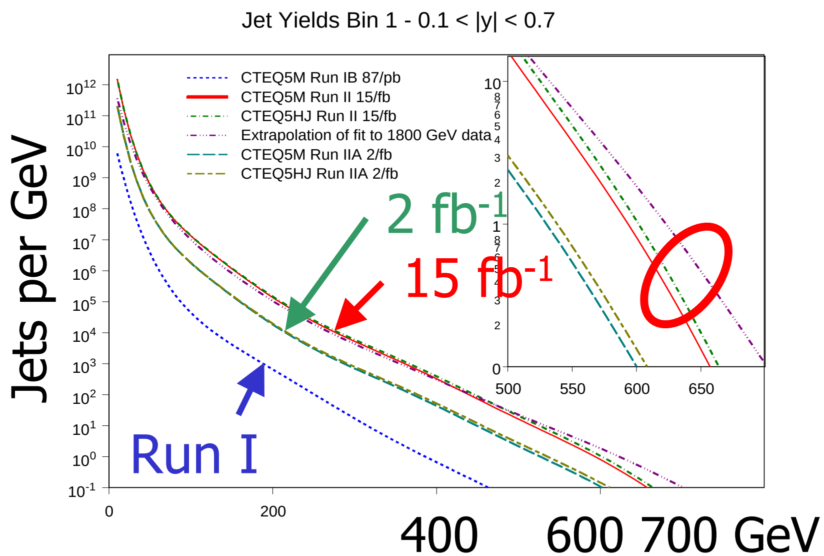
- **Other electroweak measurements**
  - **Multiboson production (test gauge couplings)**
  - **Boson plus jets**
  - **…**

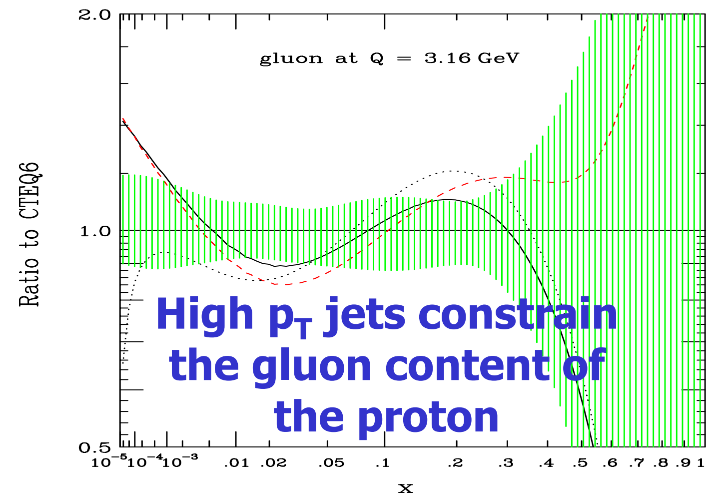
QCD

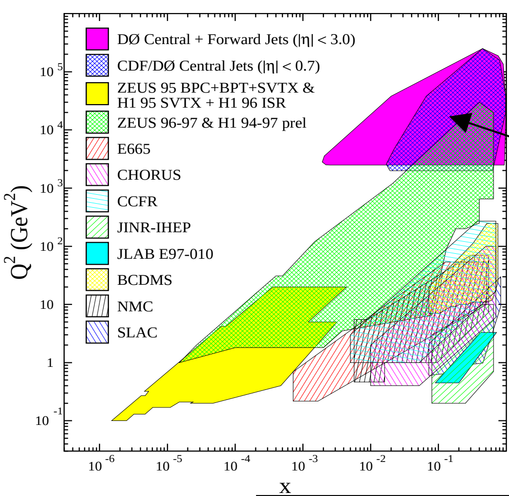
- No one doubts that QCD describes the strong interaction between quarks and gluons
  - Its effects are all around us:
    - masses of hadrons (stars and planets)
  - But it is not an easy theory to work with

- Use the Tevatron to
  - Test QCD itself
  - Understand some outstanding puzzles from Run I
  - Develop the expertise to calculate, and confidence in, the backgrounds to new physics
    - Excellent interaction between the experimental and phenomenology communities

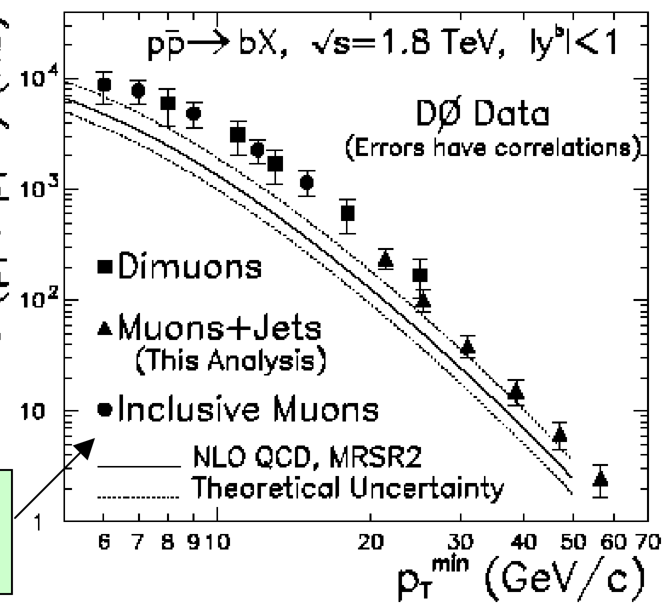
Some QCD Physics goals for Run II





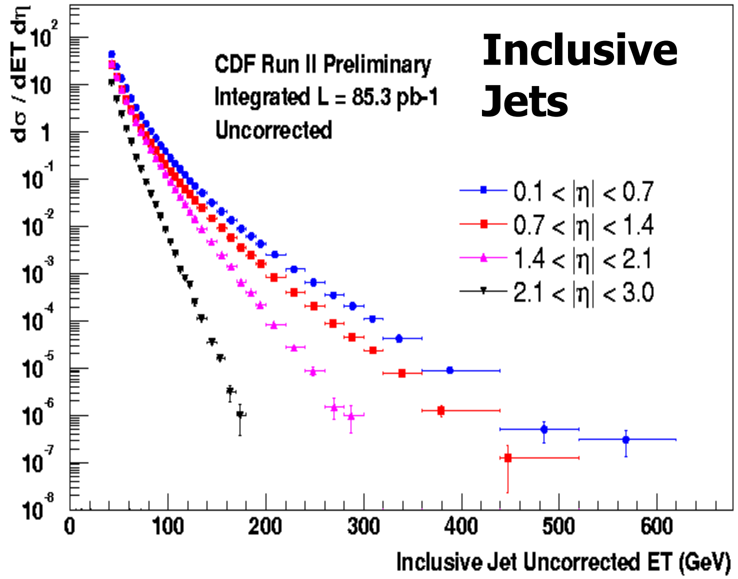


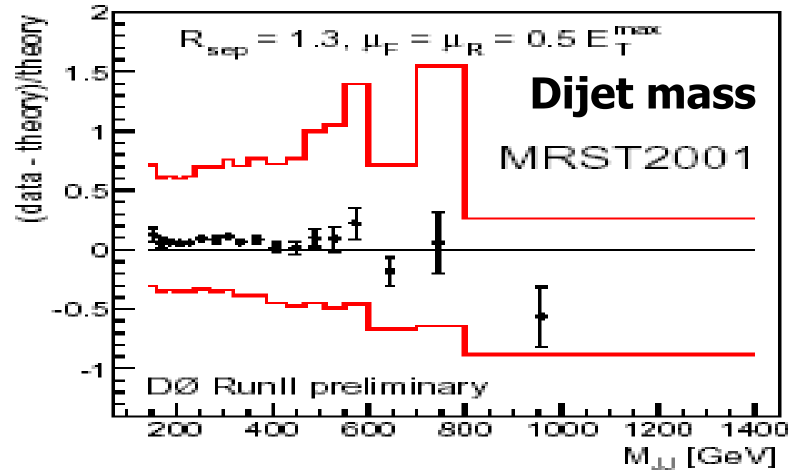
Run I jet data already used in CTEQ6 and MRST2001 parton distribution fits; complements HERA's kinematic range



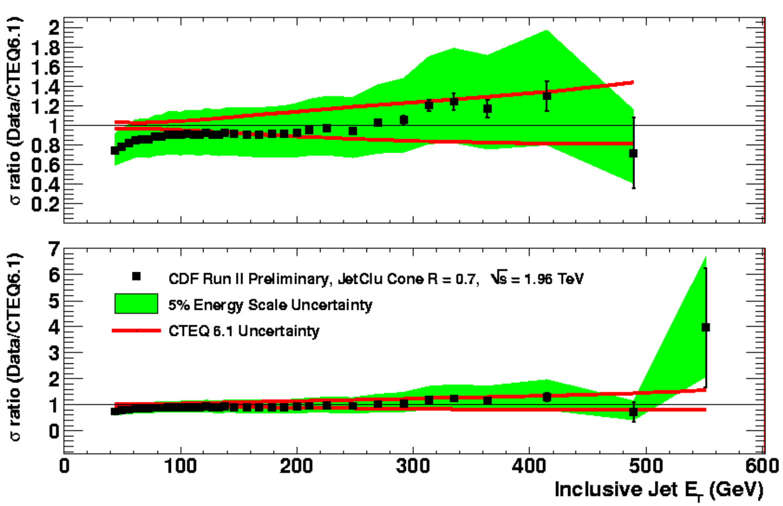
b-jet cross section
Important background to new physics

Jets in Run II

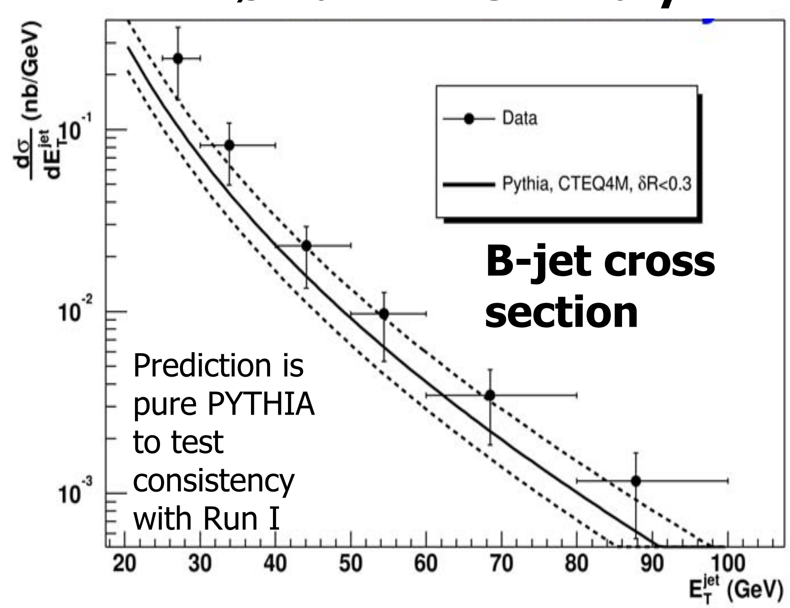




CDF Run II Preliminary



DØ Run II Preliminary



Searches for New Physics

- The Tevatron, as the world's highest energy collider, is the most likely place to directly discover a new particle or force
- We know the SM is incomplete
  - Most popular extension: supersymmetry
- Predicts multiple Higgs bosons, strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos and neutralinos
  - masses depend on unknown parameters, expected to be 100 GeV - 1 TeV

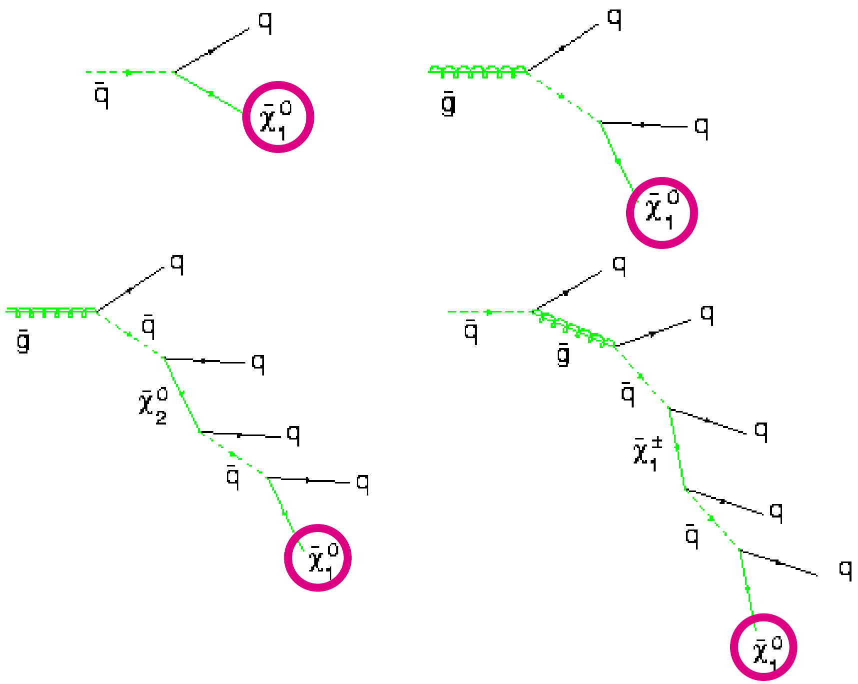
Lightest neutralino is a good candidate for cosmic dark matter
Potentially discoverable at the Tevatron

Supersymmetry signatures

- **Squarks and gluinos are the most copiously produced SUSY particles**
- **As long as R-parity is conserved, cannot decay to normal particles**
  - **Jets plus missing transverse energy signatures**

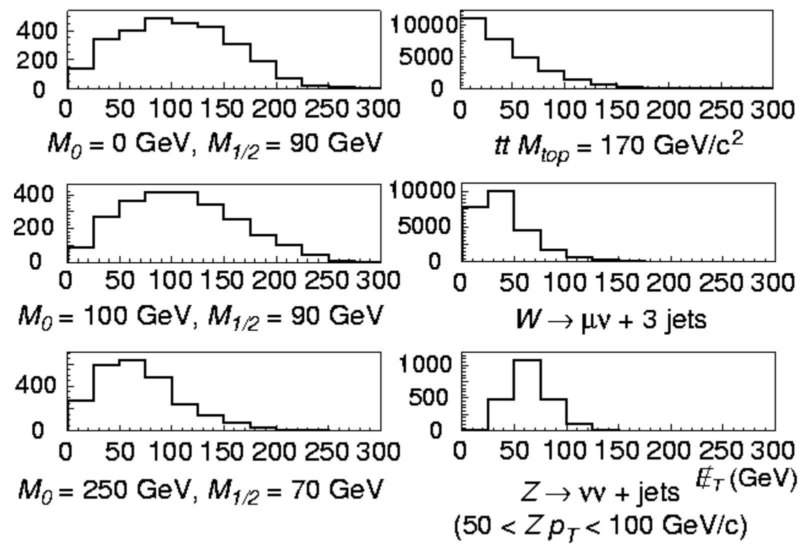
Make dark matter at the Tevatron! → **Detect its escape from the detector**

Possible decay chains always end in the LSP



Missing E_T

SUSY **backgrounds**



Search region typically > 75 GeV

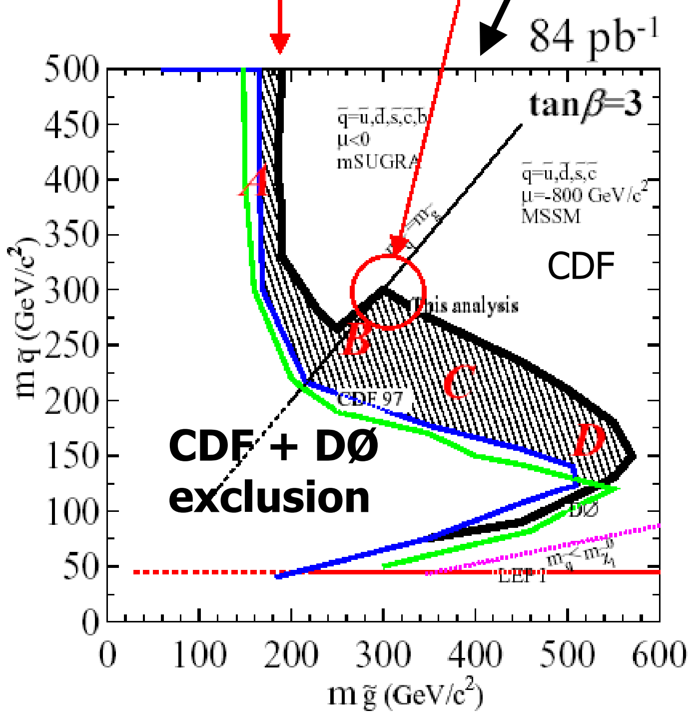
Searching for squarks and gluinos

Run I

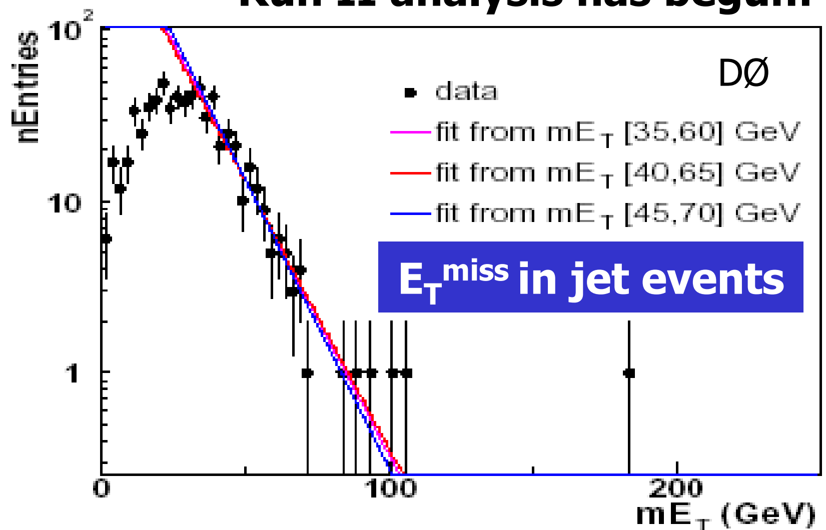
$M_{\tilde{g}} > 300\ \mathrm{GeV/c^2}$ $M_{\tilde{q}} \approx M_{\tilde{g}}$

$M_{\tilde{g}} > 195\ \mathrm{GeV/c^2}$

With 2 fb^{-1}:
Reach in gluino mass ~ 400 GeV



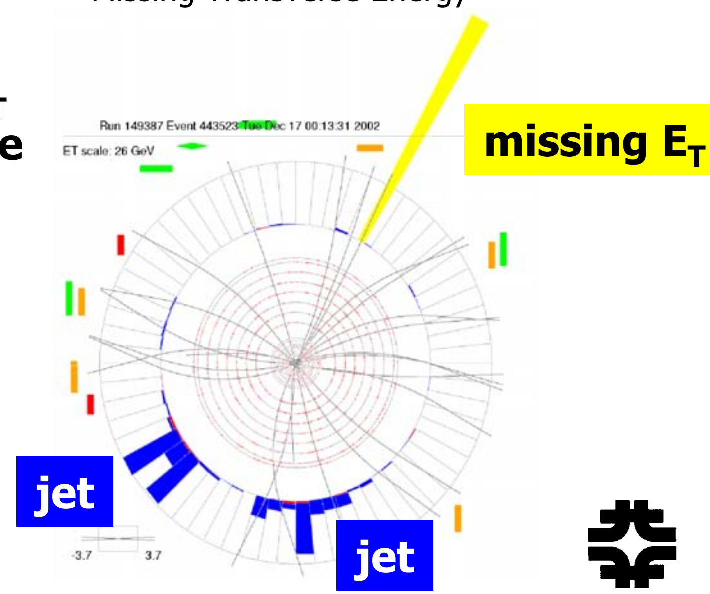
Run II analysis has begun:



Missing Transverse Energy

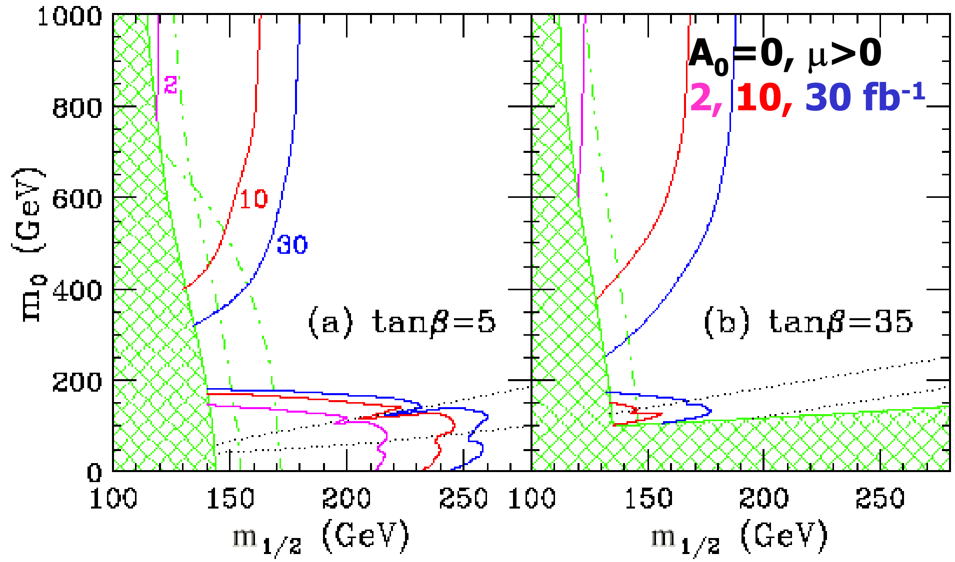
High ME$_T$ candidate event

DØ

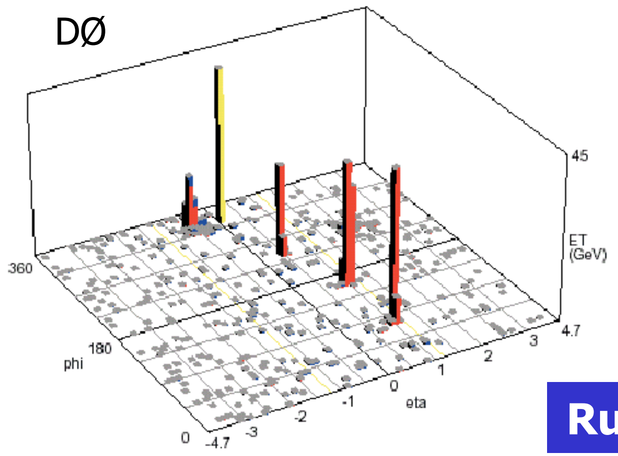


Chargino/neutralino production

- "Golden" signature
  - Three leptons
    - very low standard model backgrounds
- This channel becomes increasingly important as squark/gluino production reaches its kinematic limits (masses ~ 500 GeV)



- Reach on $\chi^{\pm}$ mass, $2fb^{-1}$ ~ 180 GeV ($\tan\beta = 2, \mu < 0$)
  ~ 150 GeV (large $\tan\beta$)

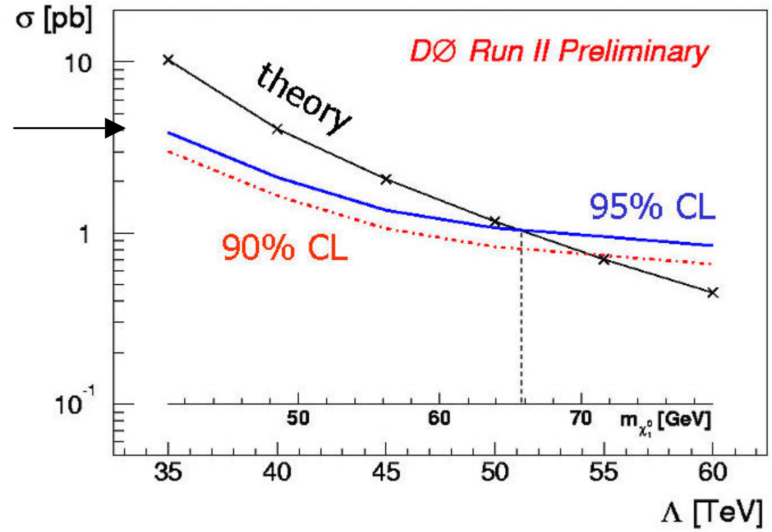


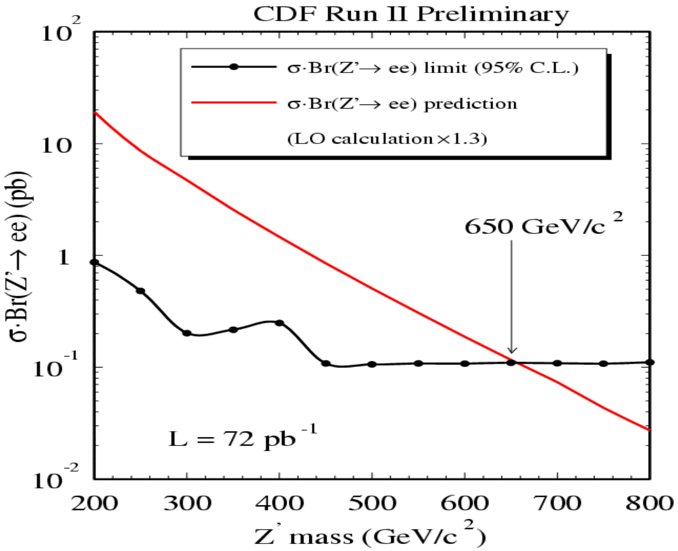
Run II Trilepton candidate

Searches have begun.
So far number of events is consistent with expectations — we need a lot more data, but the tools are in place

Other Searches at the Tevatron

- Other Tevatron search channels for SUSY
  - GMSB $\rightarrow$ Missing E_T + photon(s)
  - Stop, sbottom
  - RPV signatures
- Searches for other new phenomena
  - leptoquarks, dijet resonances, W',Z', massive stable particles, doubly charged particles…



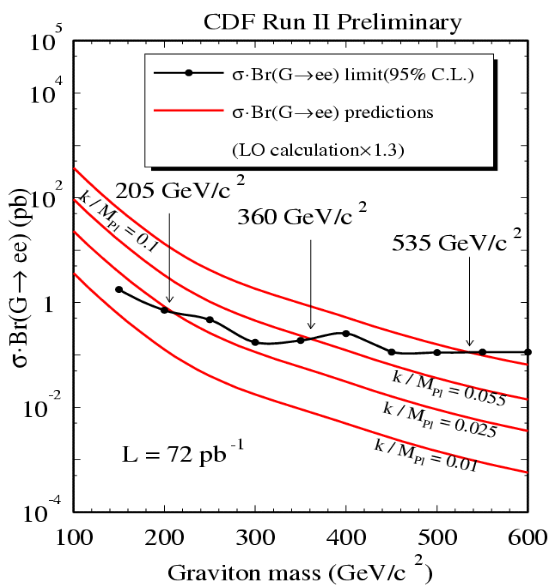


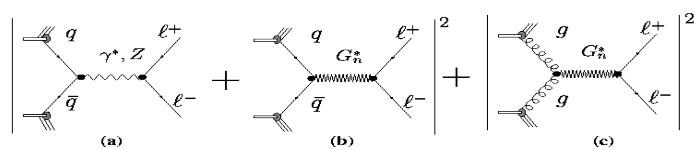
Several search results already comparable or better than Run I

CDF Run II Z' > 650 GeV/c^2

Extra Dimensions

- **Run II is also testing the new and exciting idea of extra dimensions**
  - **Can gravity propagate in more than four dimensions of space-time?**
  - **If these dimensions are not open to the other SM particles and forces, we would not perceive them**
  - **Particle physics experiments at the TeV scale could see effects (direct and indirect)**
    - **Measure the structure of space-time!**

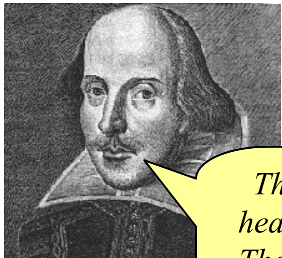




	GRW	HLZ for n: 2	7	Hewett $\lambda = +1$
diEM	**1.12**	**1.16**	**0.89**	**1.00**
diMU	**0.79**	**0.68**	**0.63**	**0.71**

DØ
Run II
Preliminary

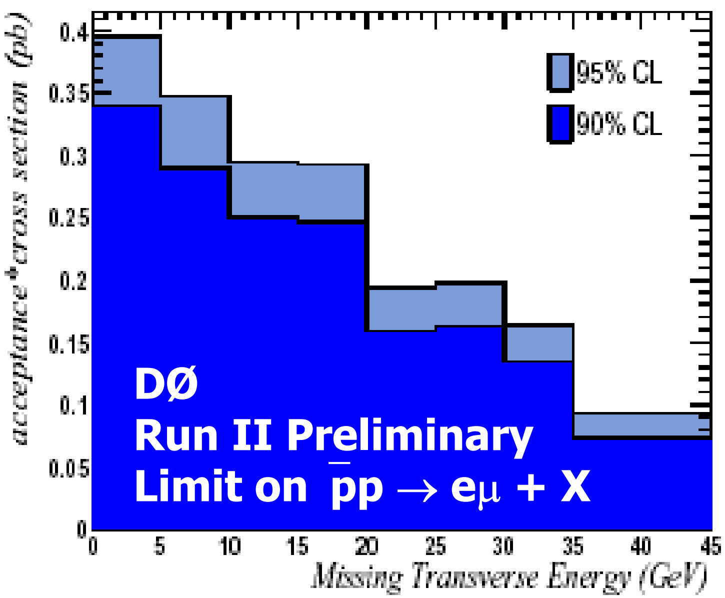
With 300 pb^{-1}, we probe up to 1.6 TeV
With 2 fb^{-1}, we probe up to 2 TeV



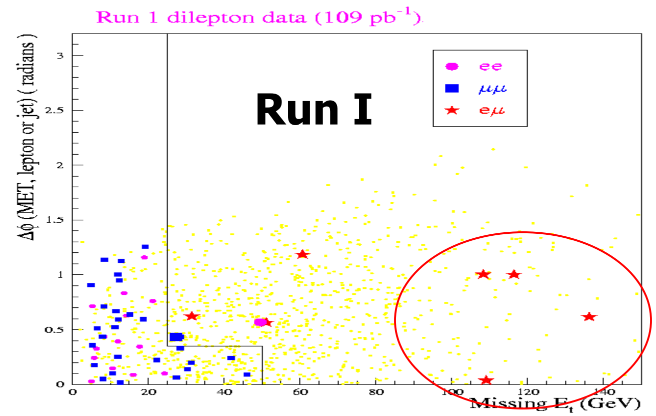
There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy.

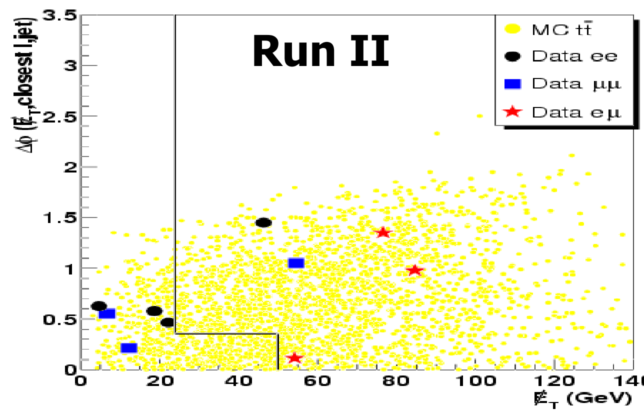
Signature-based searches

We need to ensure that our searches are not constrained by our preconceptions of what might be "out there."



CDF dilepton top events





Follow up anomalies in Run I data, and set model-independent limits

"Sleuth" framework used very successfully by DØ

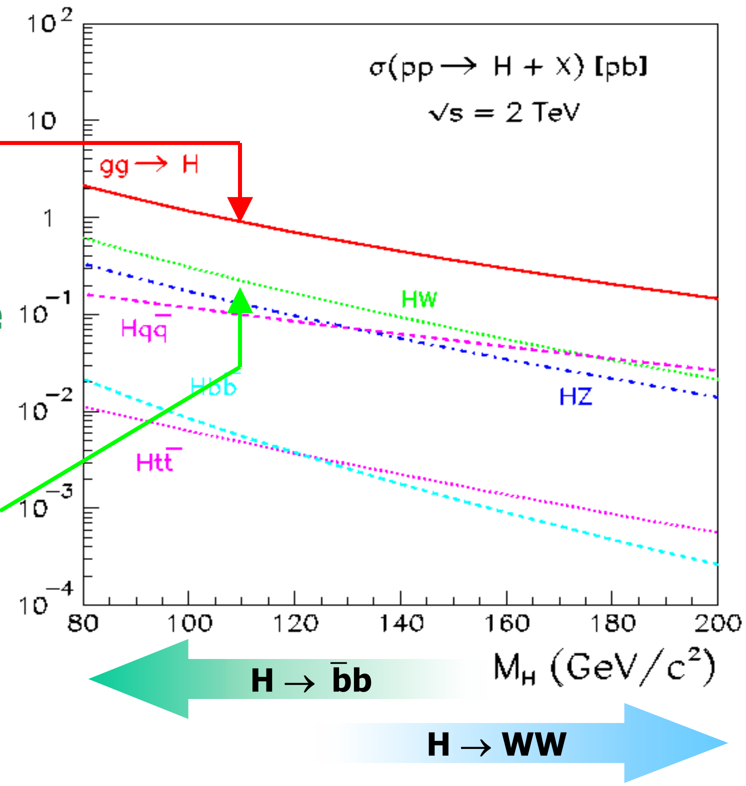
Phys. Rev. D {62} 92004 (2000)

The Higgs Boson

- In the Standard model, the weak force is weak because the W and Z gain mass from a scalar field that fills the universe
- The same field is responsible for the mass of the fundamental fermions
- If it exists, we can excite the field and observe its quanta in the lab
  - The Higgs boson
    - Last piece of the SM
    - Key to understanding beyond-the-SM physics like supersymmetry: a light Higgs is a basic prediction of SUSY
- All the properties of the Higgs are fixed in the SM with the exception of its own mass: simulations have no free parameters

Higgs Hunting at the Tevatron

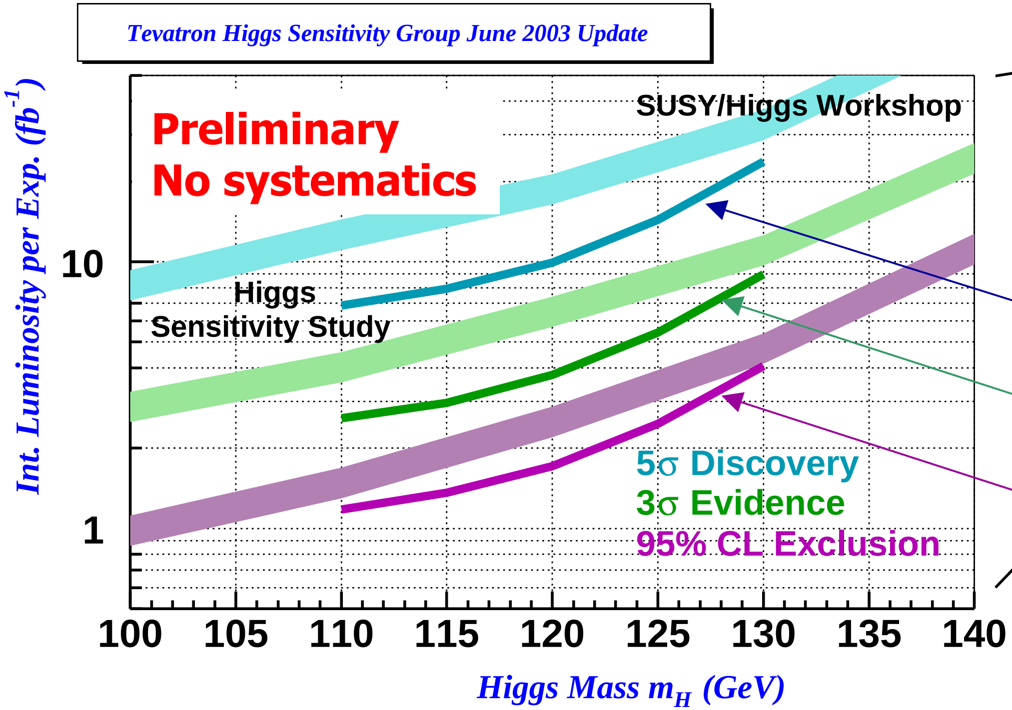
- For any given Higgs mass, the production cross section and decays are all calculable within the Standard Model
- Inclusive Higgs cross section is quite high: ~ 1pb
  - for masses below ~ 140 GeV, the dominant decay is H → bb which is swamped by background
  - at higher masses, can use inclusive production plus WW decays
- The best bet below ~ 140 GeV appears to be associated production of H plus a W or Z
  - leptonic decays of W/Z help give the needed background rejection
  - cross section ~ 0.2 pb

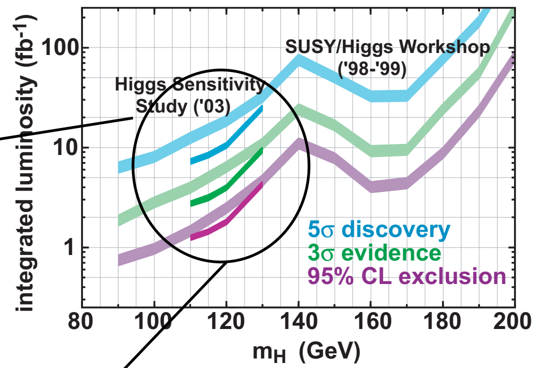


Dominant decay mode

Preliminary update on Higgs sensitivity

- A CDF + DØ joint study has updated the "famous" reach plot:

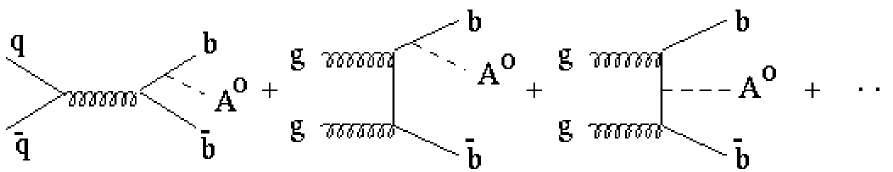




- Concentrate on low mass region (favored both in SM and SUSY)
- The Higgs reach at the Tevatron appears to be at least as good as was projected four years ago
- Our understanding will continue to improve

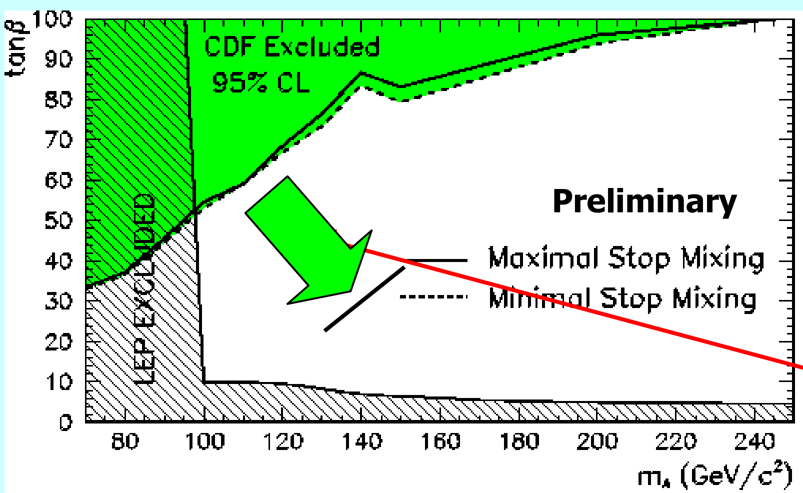
SUSY Higgs Production at the Tevatron

- bb(h/H/A) enhanced at large tan β:

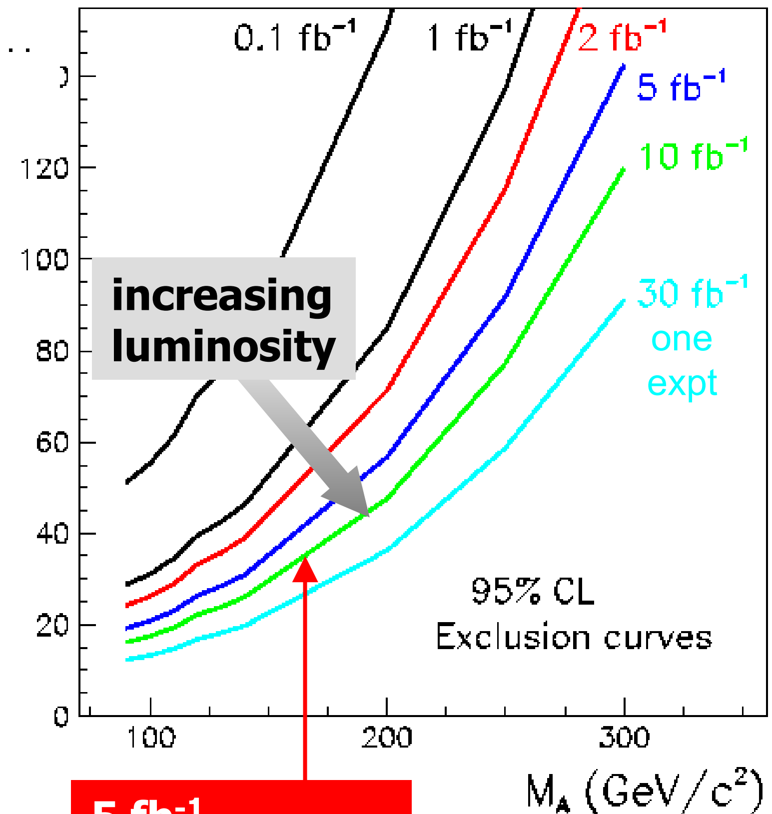


- $\sigma \sim 1$ pb for tanβ = 30 and m_h = 130 GeV

CDF Run I analysis (4 jets, 3 b tags) sensitive to tan β > 60



bb(h/A) $\rightarrow$ 4b



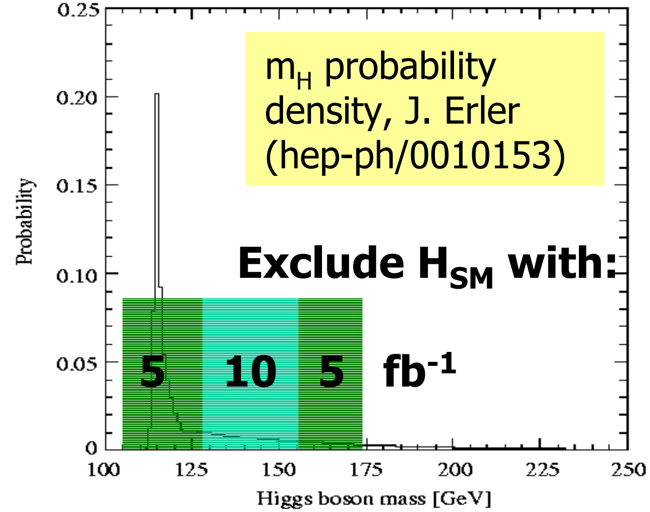
5 fb^{-1}
m_A =140 GeV,
tan β = 30

What if we see nothing?

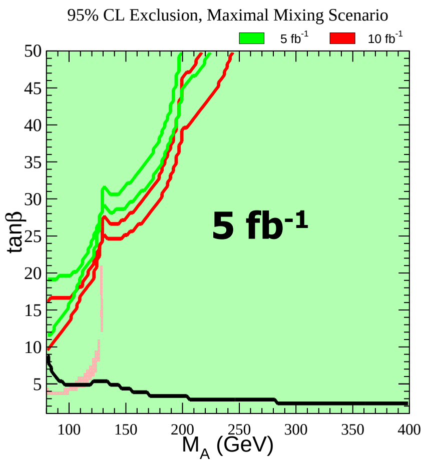
Exclusion of a Higgs would itself be a very important result for the Tevatron

- In the SM, can exclude most of the allowed mass range with 10 fb^{-1}
- In the MSSM, can potentially exclude
  <u>all</u> the remaining parameter space with 5 - 10 fb^{-1}
- Would certainly make life "interesting" for SUSY at the TeV scale

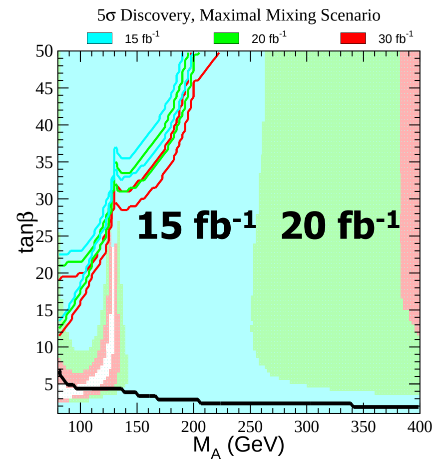
Note: these plots do not yet take account of the Higgs reach update



95% exclusion



5σ discovery



Exclusion and discovery for SUSY Higgs sector, maximal stop mixing, sparticle masses = 1 TeV

Conclusions

- **The Run II physics program has begun**
  - **We now have more data than Run I, taken at a higher CM energy with better detectors**

- **The combination of highest accelerator energy, excellent detectors, enthusiastic collaborations, and data samples that double every year guarantees interesting and important new physics results at every step.**

- **Each step answers important questions, and each step leads on to the next**

- **The collaborations are committed to**
  - **Maximize this physics program**
  - **Exploit the full potential of the world's highest energy collider and the large investments we have made in the accelerator and detectors**
  - **Lay a firm foundation for the LHC and for future initiatives at the TeV scale**

- **We believe these goals**
  - call for a robust effort to deliver luminosity of order 10 fb^{-1} by the time LHC starts to produce physics
  - require the silicon detectors be upgraded to exploit the full luminosity